Multiple Scattering of Sound by Internal Waves and Acoustic Characterization of Internal Wave Fields in Deep and Shallow Water

Oleg A. Godin
CIRES/Univ. of Colorado and NOAA/OAR/Environmental Technology Lab., R/ET-0, 325 Broadway, Boulder, CO 80305-3328
phone: (303) 497-6558 fax: (303) 497-3577 email: oleg.godin@noaa.gov

Alexander G. Voronovich
NOAA/OAR/ Environmental Technology Lab., R/ET1, 325 Broadway, Boulder, CO 80305-3328
phone: (303) 497-6464 fax: (303) 497-3577 email: alexander.voronovich@noaa.gov

Document Numbers: N00014-05-IP2-0024 and N00014-03-IP2-0085
http://www.etl.noaa.gov

LONG-TERM GOALS

- To improve understanding of the effects of internal waves (IWs) on sound propagation underwater.

- To develop an empirical statistical description of IWs in shallow water

- To measure acoustically path-averaged energy of IWs in the ocean and variations of the energy on time scales from hours to years.

- To develop a comprehensive model of the IW spectra in the deep ocean and their regional and temporal variability.

OBJECTIVES

1. To extend the existing theory of 3-D and 4-D acoustic effects induced by IWs to the regime of strong sound scattering.

2. To model the frequency shift and spectrum broadening of CW sound scattered by spatially-diffuse, random IWs in deep and shallow water.

3. To develop a predictive model of the acoustic frequency evolution at sound scattering by a train of tidally-generated, nonlinear IWs in a coastal ocean.

4. To assess the feasibility of inverting a measured frequency spectrum of the sound emitted by a narrow-band source, for spatially-averaged parameters of the IW fields in shallow and deep water.

5. To develop a theoretical description and a computer model of the average acoustic field in a deep ocean in the presence of a statistical ensemble of IWs.

Report Documentation Page

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Multiple Scattering of Sound by Internal Waves and Acoustic Characterization of Internal Wave Fields in Deep and Shallow Water**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Technology Lab,CIRES/Univ. of Colorado and NOAA/OAR,R/ET-0, 325 Broadway,Boulder,CO,80305**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

6. To perform numerical simulations of the inversion of the mean acoustic field for IW characteristics and determine optimal parameters of the corresponding field experiment.

APPROACH

Three complementary representations of the acoustic field are used in this work, namely, the ray-theoretical description of the field, full-wave representation of the field in the normal-mode basis, and the parabolic approximation.

A simple, convenient, and computationally efficient description of forward sound scattering by 3-D inhomogeneous, time-dependent sound speed fluctuations can be obtained by using the ray perturbation theory (Godin et al., 2005). The theory accounts for the change in geometry of 4-D (i.e., space-time) rays due to small fluctuations in the sound speed, and allows one to express first- and second-order perturbations in travel time, arrival angles, pressure amplitude, and other acoustic observables as integrals of weighted environmental perturbations calculated along unperturbed rays. When IW-induced sound speed variations are viewed as random fluctuations superimposed on a deterministic background, the theory expresses statistical moments of acoustic observables in terms of integrals of appropriate statistical moments of environmental perturbations. The integrals are calculated along unperturbed rays. Predictions of the analytical theory will be verified against Monte Carlo simulations of sound propagation.

For a full-wave analytic description of 3-D and 4-D acoustic effects in the strong perturbation regime, where the spatial displacements of acoustic trajectories due to IW-induced perturbations are comparable to or larger than the correlation length of the environmental perturbations, Chernov's "local method" will be used in conjunction with the Markov approximation. This will allow us to evaluate second moments of the acoustic filed. With this technique, only smallness of scattering on the correlation radius of the inhomogeneities is required. This condition is fulfilled for practical situations and for frequencies on the order of a hundred Hertz, however it can be violated at higher frequencies. In this case, standard diagrammatic technique can be used for calculation of the average field. This approach requires fluctuations of the index of refraction to be Gaussian, which is a good approximation in many practical situations. The equation for the average acoustic field in the statistically homogeneous in horizontal plane stratified waveguide satisfies an integral-differential equation. The kernel of the integral operator is calculated as a power series in the standard deviation of the refraction index. In the lowest order (Burret approximation), the kernel is proportional to the spectrum of fluctuations. This equation also determines specific "average field" modes which generally can be different from the standard acoustic modes.

The key individuals that has been involved in this work are Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ETL) and Alexander G. Voronovich and Valery U. Zavorotny (NOAA/ETL). Dr. Voronovich has been primarily responsible for developing full-wave theoretical descriptions of multiple scattering of sound by internal gravity waves. Dr. Zavorotny has been involved in numerical simulations of the acoustic field and contributed his expertise on waves in random media. Dr. Godin took the lead in the theory and modeling of the 3-D and 4-D effects in underwater sound propagation.

WORK COMPLETED

A simple and efficient approach based on the reciprocity principle has been developed for calculation of amplitudes of the discrete (proper normal modes) and continuous (improper normal modes) spectra of the acoustic field in a waveguide (Godin, 2005).

Validity of Fermat's principle of stationary optical path length has been established for a class of dispersive waves, such as adiabatic acoustic normal modes in an underwater waveguide, in environments with time-dependent parameters (Godin and Voronovich, 2005).

Role of finite-frequency effects in excitation of natural waveguides by sound sources on the ocean surface and in generating ambient noise has been quantified (Godin and Naugolnykh, 2005).

A technique (Godin et al., 2005) for propagation of the first and second statistical moments of acoustic observables that characterize 3-D and 4-D acoustic effects in the ocean has been extended to include calculation of correlations of the observables at points separated in space and time.

The Dyson equation for the average acoustic field was derived using diagrammatic technique similar to the one used in the theory of wave propagation in the homogeneous medium. The mass operator was calculated in the Bourret approximation in terms of the modal spectrum of internal waves.

The Dyson equation was analyzed and the expressions for the decrements of attenuation of the average acoustic field were obtained in both 2-D and 3-D cases.

The statistical criterion of the validity of the 2-D approximation to the fully 3-D propagation model was derived.

Computer codes for calculation of acoustic mode-coupling matrix at sound scattering on a normal mode of internal gravity waves were developed.

With funds from a grant N00014-03-IP2-0085 to support a publication in English of a Russian multi-author volume on the history of Soviet and Russian underwater acoustics, translation was completed of the original Russian book and the additional review articles commissioned for the English edition. The translation was made by translators based in Russia and has been edited by Dr. D. R. Palmer of NOAA/AOML (Miami, FL) who is an English native speaker and an expert in underwater acoustics. Scientific fidelity of the translations has been verified by Dr. O. A. Godin and some of the authors of key contributions. Publication proposals have been sent to a number of commercial publishers active in the field of underwater acoustics. Of the three publishers which expressed interest in publication of *History of Russian Underwater Acoustics*, World Scientific Publishing Co. (Singapore) offered the best terms, including rapid publication of an unabridged text and world-wide dissemination. Drs. Godin and Palmer entered into publication agreement with World Scientific Publishing Co. as editors of the English translation. The book is expected to become available in 2006.

RESULTS

Propagation of statistical moments of acoustic variables provides efficient means to study acoustic implications of various descriptions of environmental fluctuations. WKB-type simplifications of the

Garrett-Munk spectrum are employed in many internal wave models and sound scattering theories. These simplifications are shown to result in significant underestimation (Figure 1) of the acoustically relevant characteristic B of cross-range sound speed gradients which are responsible for IW-induced random horizontal refraction. The quantity B is defined in terms of a correlation function of sound-speed fluctuations W as (Godin et al., 2005)

$$B(\chi, z) = \frac{-1}{2\cos\chi} \int_{-\infty}^{+\infty} \frac{\partial^2 W}{\partial y^2}(x, y, x\tan\chi; z)\bigg|_{y=0} dx.$$

Here x and y are horizontal coordinates, z is a vertical coordinate, and χ is grazing angle.

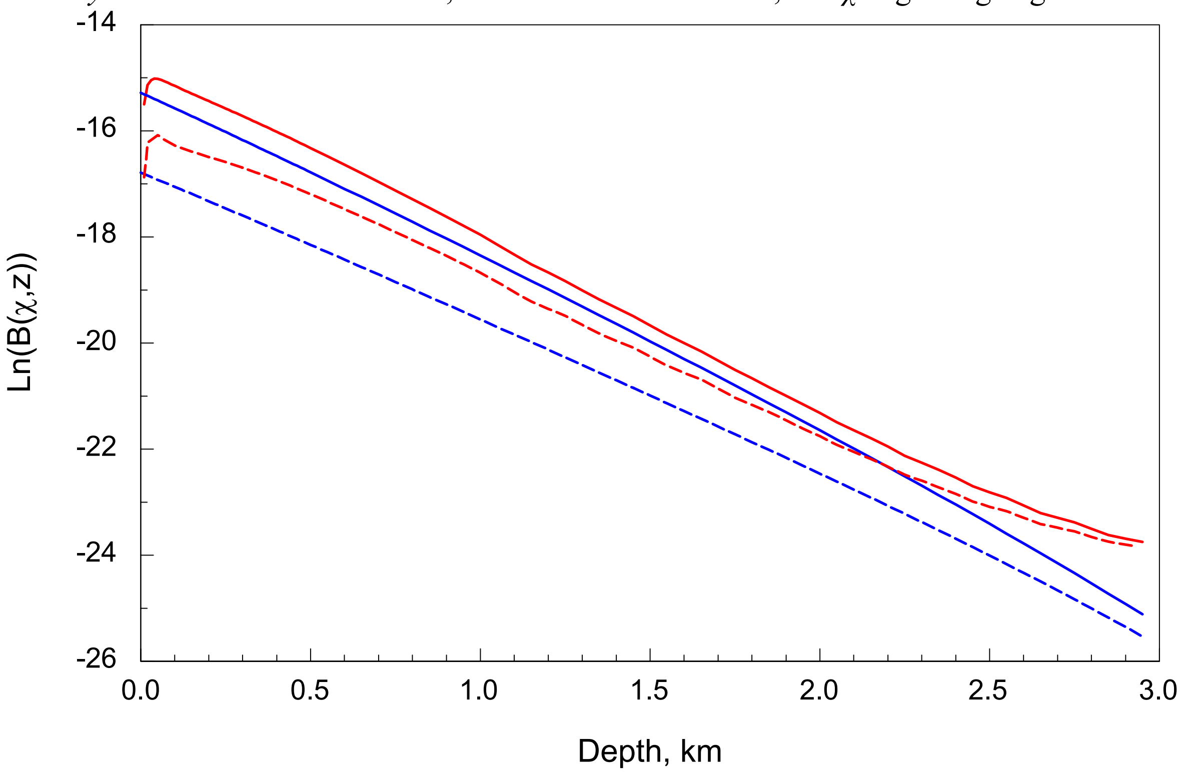

Figure 1. Depth dependence of an acoustically relevant characteristic, B, of internal-wave induced cross-range sound-speed gradients. The quantity B is calculated using either a rigorous implementation of the Garrett-Munk spectrum in terms of modes of internal waves (red) or a traditional, simplified version of the spectrum (blue) for two grazing angles: χ = 0 (solid lines) and χ = 20° (dashed lines).
[ln B ranges from -26 to -13. The simplified model of the internal wave field systematically underestimates sound speed gradients.]

With B calculated from a rigorous implementation of the Garrett-Munk spectrum in terms of modes of internal waves, RMS bearing errors due to random horizontal refraction over 1Mm path reach 0.38°and 0.32°, when IWs with horizontal spatial scales greater than l_{min} = 125 m and 250 m are taken into account, respectively (Figure 2). With a fixed propagation range, the minimum spatial scale of random environmental inhomogeneities that contribute to B is determined by sound frequency; l_{min} decreases and horizontal refraction intensifies when sound frequency increases. Corresponding simulations with a simplified model of the IW field give RMS bearing errors that do not exceed

0.29°and 0.27° in the high- and low-resolution cases, respectively (Figure 2). The simplified IW model underestimates both the magnitude of random horizontal refraction and its frequency dependence.

Similar discrepancies have been found between statistical moments of other acoustic observables calculated using rigorous and simplified implementations of the Garrett-Munk spectrum. These results suggest that care should be taken in accurately describing details of internal wave spectrum if acoustic measurements are to be used to characterize spatially-averaged absolute strength of internal waves in the ocean.

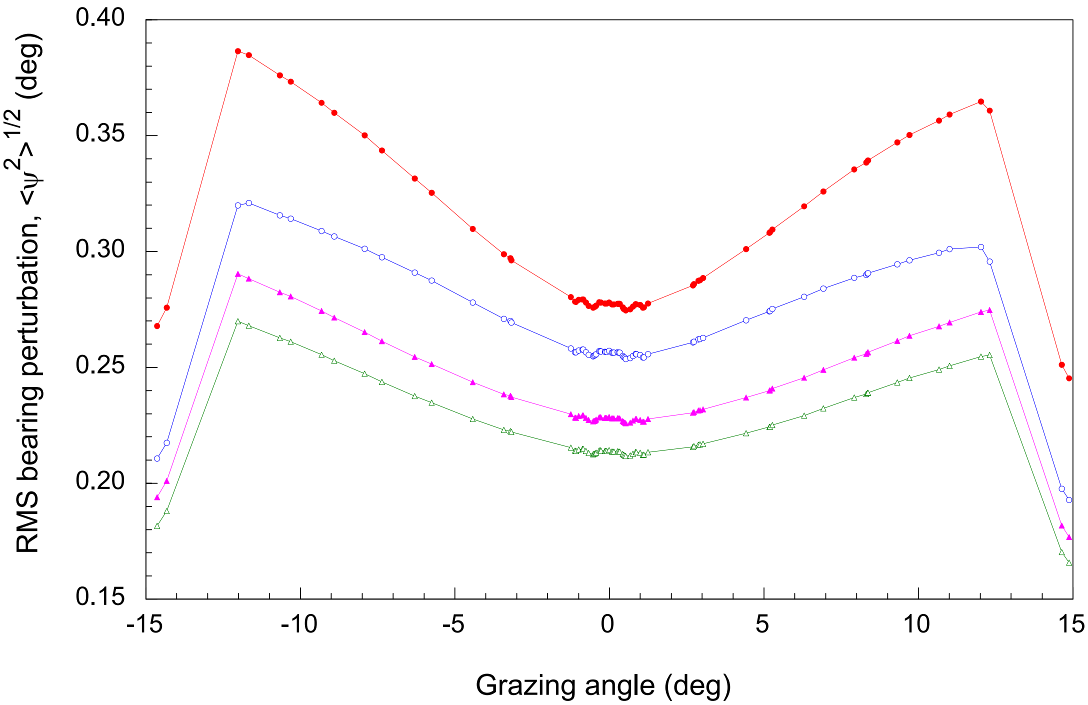

Figure 2. RMS bearing perturbations on various eigenrays due to the horizontal refraction induced by internal waves with the Garrett-Munk spectrum: rigorous internal wave model with high (red) and low (blue) resolution and a simplified internal wave model with high (pink) and low (green) resolution. Source and receiver are on the axis of the canonical sound speed profile. Propagation range is 1000 km.
[Bearing errors range from 0.16° to 0.39° and are greater for more structured internal wave field. Simplification of the spectrum results in underestimating the bearing errors by as much as 40%.]

It has been demonstrated that the average acoustic field for the Gaussian, horizontally homogeneous statistics of the refraction index of the acoustic waveguide satisfy a linear integral-differential equation. The non-local (mass) operator is represented as a sum of corresponding irreducible diagrams which describe interactions between the acoustic and IW modes. The Fourier transform of this equation results in a 1-D equation with respect to vertical coordinate which consists of the standard differential vertical operator and an integral term. Thus, acoustic modes corresponding to the average field are generally different from the standard acoustic modes. The expression for the average Green function to the lowest order in perturbation parameter coincides with the standard expression, but with the propagation constants having imaginary parts which represent the decrement of attenuation of the corresponding acoustic mode. The explicit expression for the decrement of attenuation in terms of the IW spectrum is obtained. Both 2-D and 3-D cases are considered. It is demonstrated that the possibility of neglecting 3-D effects depends on the shape of the IW spectrum and also requires sufficient smoothness of the sound speed fluctuations with respect to depth.

The computer code for calculation of the decrements of attenuation of the acoustic modes has been developed. Preliminary estimates show that the decrement strongly depends on mode number and for 65 Hz acoustic frequency can vary from hundreds to many thousands of kilometers. The decrement decreases for higher acoustic modes.

IMPACT/APPLICATIONS

Strong dependence of the modal decrements of the average field attenuation on the acoustic mode number provides a possibility to use this dependence for retrieving the spatial spectrum of internal gravity waves from measurements of the average acoustic field with long vertical receiving arrays. Knowledge of the mode-number dependence of the decrements also provides an opportunity to improve the quality of acoustic transmissions in the ocean by proper selection of the carrier acoustic modes.

RELATED PROJECTS

Low-frequency, long-range sound propagation through a fluctuating ocean: Analysis and theoretical interpretation of existing and future NPAL experimental data (N00014-04-IP2-0009.)

REFERENCES

Godin O. A., Zavorotny V. U., Voronovich A. G., and Goncharov V. V. Refraction of sound in a horizontally-inhomogeneous, time-dependent ocean, *IEEE J. Oceanic Engineering,* **30**, No. 2 (2005)

PUBLICATIONS

O. A. Godin, Review of *Reciprocity in Elastodynamics* by J. D. Achenbach (Cambridge Monographs on Mechanics, Cambridge University Press (2003)), *J. Sound Vibr.* **284**, No. 3-5, p. 1249-1252 (2005) [published]

O. A. Godin, Calculation of amplitudes of acoustic normal modes from the reciprocity principle, *J. Acoust. Soc. Am*. (2005) [in press, refereed]

O. A. Godin and A. G. Voronovich, Fermat's principle for dispersive waves in nonstationary media, *Proceedings of the International Seminar Days on Diffraction 2005 (Saint Petersburg, Russia, June 28 - July 1, 2005)*

O. A. Godin and K. A. Naugolnykh, Guided propagation of naturally occurring infrasound in troposphere and stratosphere, *Geophys. Research Lett.* (2005).